Final Technical Report

Collaborative Research with Caltech and Harvard University: Predicting strong ground motions for large earthquakes in southern California using the spectral element method

Award 04HQGR0064

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Program Element I

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NON-TECHNICAL SUMMARY
Our research focused on developing better methods for predicting strong ground motions that will result from large earthquakes in southern California using a powerful numerical technique (Spectral-Element Method) and new structural models. In this study, we improved the models using additional borehole and seismic reflection data, generated new representations of fault surfaces, developed an automated procedure to determine earthquake source parameters, and performed simulations of the 1994 Northridge (M6.7) earthquake and a hypothetical San Andreas event. Ultimately, these efforts will improve assessments of the ground shaking hazards resulting from large earthquakes in southern California in order to reduce losses.

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TECHNICAL ABSTRACT

We have developed and implemented a spectral-element method (SEM) and constructed a new velocity model in southern California to simulate strong ground motions generated by earthquakes. The numerical simulations account for three-dimensional variations of seismic wave speeds and density, topography and bathymetry, and attenuation. Simulations for the September 9, 2001 M=4.2 Hollywood earthquake and the September 3, 2002 M=4.2 Yorba Linda earthquake demonstrate that the combination of this detailed sedimentary basin model and the SEM method facilitates the simulation of strong ground motion at periods of 2 seconds and longer (Komatitsch et al., 2004). In this study, we have improved the velocity model using new borehole and seismic reflection data, generated new representations of fault surfaces, developed an automated moment-tensor inversion procedure to determine source parameters, and performed simulations of the 1994 Northridge (M6.7) earthquake and a hypothetical San Andreas event. Peak ground displacement, velocity, and acceleration maps illustrate that significant amplification occurs within the Los Angeles and San Fernando basins as a result of these earthquakes. Ultimately, these efforts seek to improve assessments of the ground shaking hazards that will result from large earthquakes in southern California in order to reduce losses.

The SEM code and velocity model are available to the earthquake science community through websites at Caltech and Harvard University, respectively.

Caltech (http://www.gps.caltech.edu/%7Ejtromp/research/downloads.html); and

Harvard University (http://wacke.harvard.edu:8080/HUSCV.

RESULTS

Structure Models

Our numerical simulations are performed in a high-resolution velocity model of the sedimentary basins in southern California constructed from industry sonic log, density log, and stacking velocity information (Süss & Shaw, 2003). The model defines compressional velocity (v_p) structure, with derivative shear-wave velocity and density models, and is embedded in regional tomographic models (Hauksson, 2000). Within the sedimentary basins, the model is characterized by a heterogeneous, spatial varying velocity gradient with maximum velocities of about 5000 m/sec (Figure 1). Sediment velocities were interpolated using a *kriging with trend* approach, where a modeled variogram function of the data was used to define how distributed data points were weighted in interpolating a velocity value for each grid cell. Regional trends observed in the stacking velocity values were used to guide the interpolation of borehole velocities in areas with limited well control. The top basement surface was mapped in the central basin using more than 100 wells that penetrate crystalline rock, and seismic reflection profiles that imaged the basement-sediment interface. The resulting model contains a variable grid spacing, with as small as 50 m cells in the shallow sediments and coarser spacing in the deeper sediments and basement. Co-registered Vs and density models were developed based on empirical relations between these parameters and Vp, developed using formation density and dipole sonic logs.

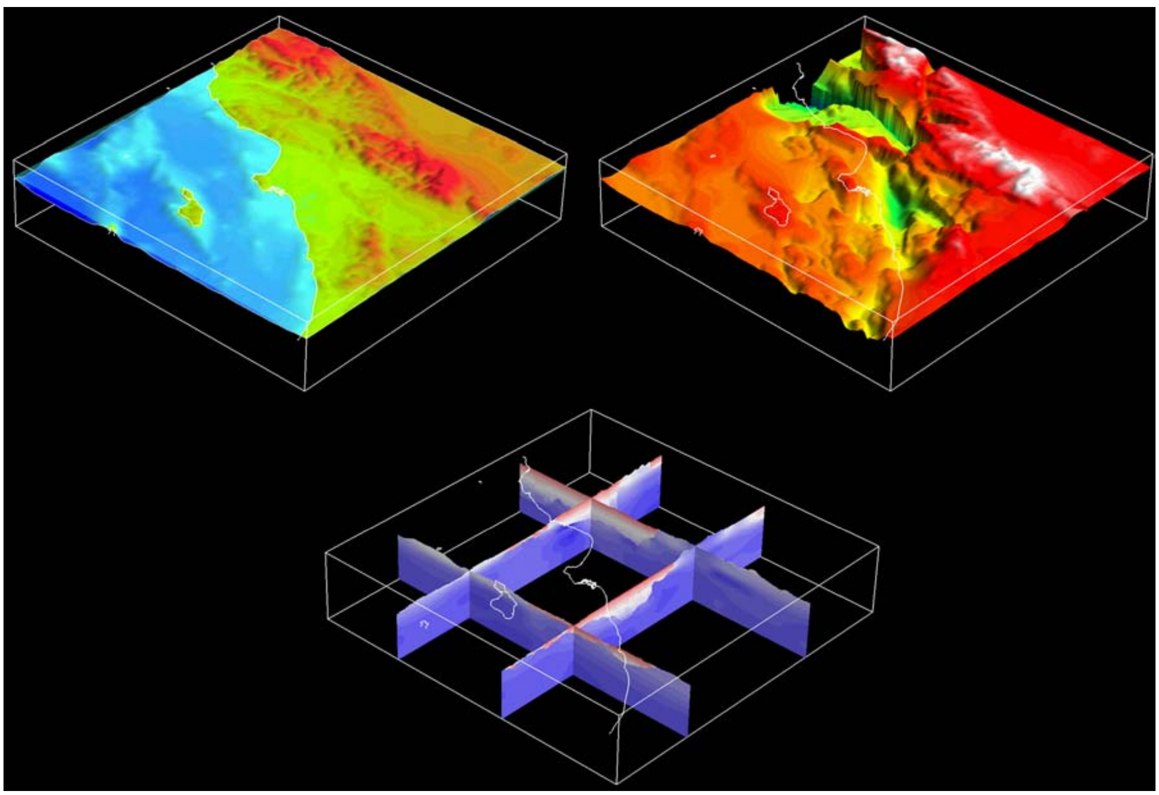


Figure 1: Perspective view of our California model (3DLAV1_HR) that is used in our simulations. (top left) Topography and bathymetry; (top right) top of crystalline basement; (lower center) cross sections with sediment velocities (red is slow, blue is fast).

In this study, we made several important upgrades to the velocity model, including extending its borders to encompass the entire study region, and improving the internal transitions between high, moderate, and low resolution regions of the model. In partnership with the Southern California Earthquake Center (SCEC), we also developed software enabling more flexible access to the model (http://wacke.harvard.edu:8080/HUSCV/). This code allows users to populate arbitrary point sets with v_p and derived shear wave velocity and density values. SCEC CME is currently planning the development of a graphical interface for this model.

In order to simulate large earthquakes, we also require three-dimensional fault representations to act as finite rupture surfaces. To this end, we have developed an improved series of triangulated surfaces for the Northridge, Puente Hills, Whittier, and San Andreas faults (Figure 2). These new fault representations include more precise lateral terminations, regular node spacings, and smoother transitions between interpolated and extrapolated fault patches. Large earthquakes are simulated by a series of sub-events located along the fault surface that in total represent the desired slip and moment distribution along the rupture surface. These new fault representations are included in the latest version of the SCEC Community Fault Model (CFM) (Plesch et al., 2004), where they have been made available to various groups performing ground motion simulations and other seismologic investigations (http://structure.harvard.edu/cfm).

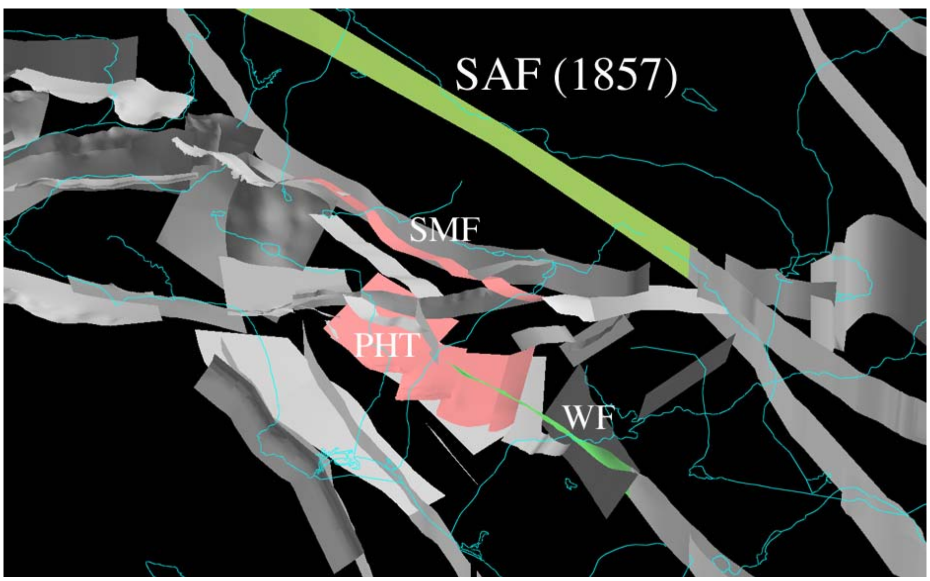


Figure 2: Perspective view of the SCEC Community Fault Model (CFM) (Plesch et al., 2004), showing 3D geometric representations of faults that are used in this study to simulate large earthquakes. The highlighted faults (SAF = San Andreas, SMF = Sierra Madre, WF = Whittier, PHT = Puente Hills thrust) offer contrasts between faults within and outside of the Los Angeles basin, and strike-slip vs. thrust faults.

Simulations

We have developed and implemented an automated moment-tensor inversion procedure to determine source parameters for southern California earthquakes. The method is based upon spectral-element simulations of regional seismic wave propagation in an integrated three-dimensional southern California velocity model. Sensitivity to source parameters is determined by numerically calculating the Frechet derivatives required for the moment-tensor inversion. We minimize a waveform misfit function, and allow limited time shifts between data and corresponding synthetics to accommodate additional 3D heterogeneity not included in our model. The technique is applied to three recent southern California earthquakes: the September 9, 2001, Mw = 4.2 Hollywood event, the February 22, 2003, Mw = 5.2 Big Bear event, and the December 14, 2001, Mw = 3.8 Diamond Bar event. An example of the transverse component waveforms for the Big Bear event is shown in Figure 3.

Using about half of the available three-component data at periods of 6 seconds and longer, we obtain focal mechanisms, depths, and moment magnitudes that are generally in good agreement with estimates based upon traditional body-wave and surface-wave inversions.

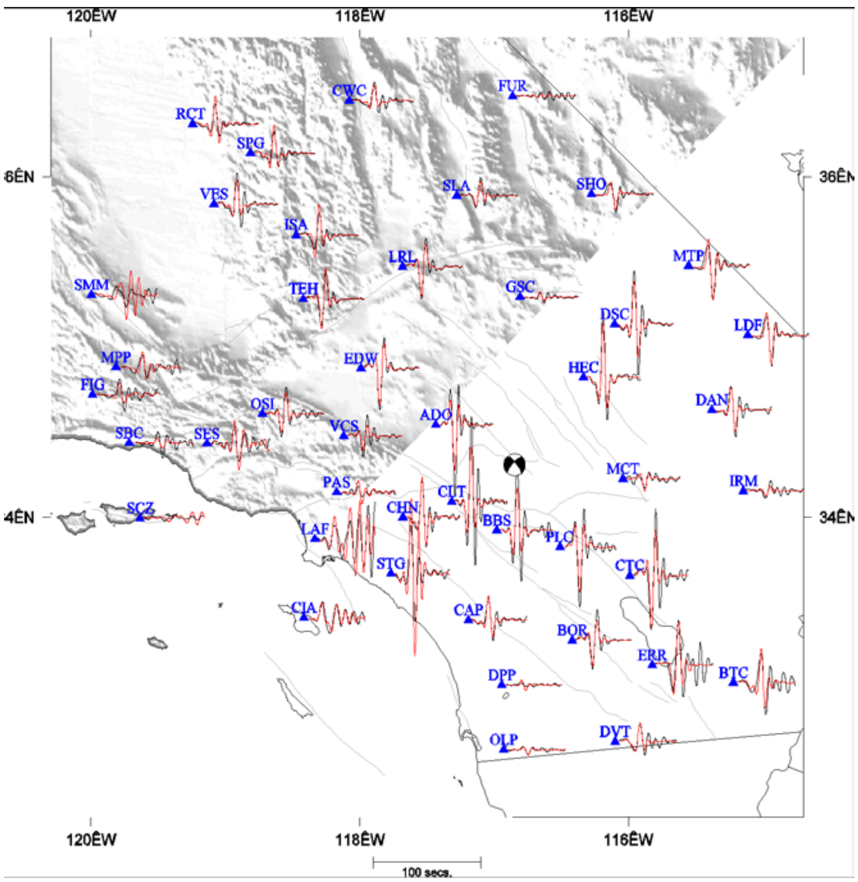
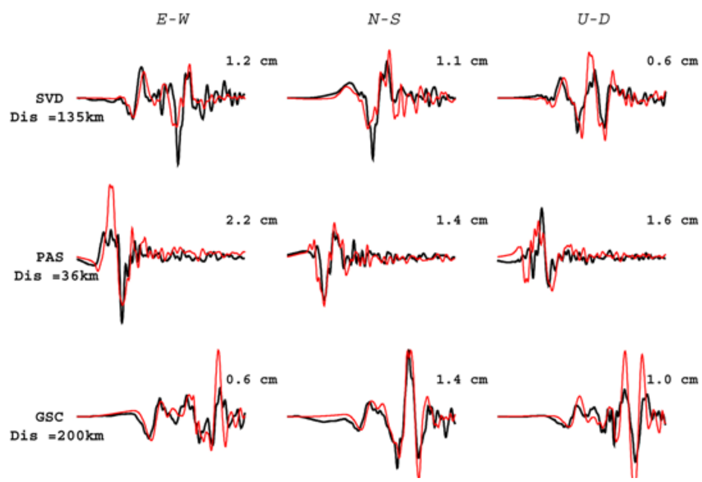


Figure 3: Selected waveform fits for transverse component data (black) and synthetics (red) for the inverted source parameters of the 22 February 2003 Big Bear main shock.

Having demonstrated that we can simulate small events in southern California quite accurately at periods longer than 2 seconds, we moved toward simulating large earthquake scenarios. Using the spectral-element seismic wave propagation code, earthquakes are simulated on regional faults and ground motions are computed at sites located on a grid with a 2.5-5.0 km spacing in the greater Southern California region. Subsequently, 3D structural models of existing and new steel buildings are analyzed for these computed ground motion records. These analyses are carried out using a nonlinear building analysis program that has the ability to simulate damage in buildings due to three-component ground motion. The performance of these structural models is summarized on contour maps of carefully selected structural performance indices. Thus far, we have performed simulations of the 1994 Northridge earthquake (Figure 4) and a hypothetical magnitude 7.9 earthquake on the San Andreas fault (SAF) using the finite source of the magnitude 7.9 2001 Denali fault earthquake in Alaska mapped onto the SAF with the rupture originating at Parkfield and proceeding southward over a distance of 290 km (Figure 5). Peak ground displacement, velocity, and acceleration maps illustrate that significant amplification occurs within the Los Angeles and San Fernando basins as a result of this simulated earthquake.



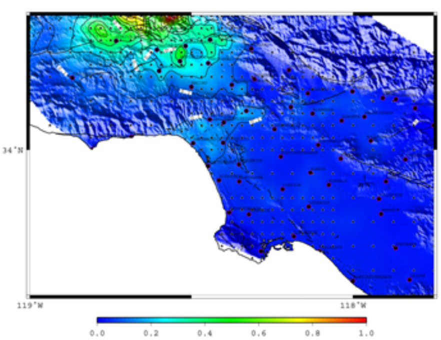


Figure 4: Left: data (black) and spectral-element method synthetics (red) for the 1994 Northridge event. We used the finite source parameters determined by Wald et al. (1996). Shown are the east-west (left column), north-south (central column) and up-down (right column) components of velocity lowpass filtered at 2 seconds. Shown are stations Seven Oaks Dam (SVD), Pasadena (PAS), Goldstone (GSC) and Domenigoni Reservoir (DGR). Right: map of simulated peak ground velocities during the 1994 Northridge event. Note the amplifications near Santa Monica and south of the Hollywood hills.

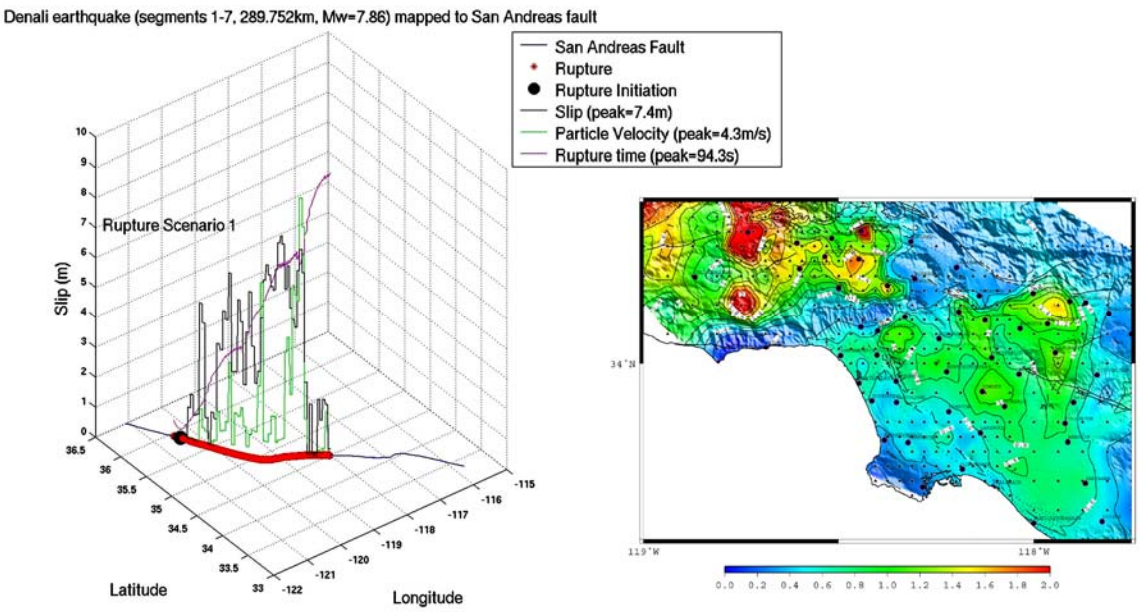


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Figure 5: Left: Finite-fault model for a hypothetical magnitude 7.9 event on the San Andreas fault based upon a kinematic fault model for the 2001 Denali earthquake. Right: Peak ground velocities in the greater Los Angeles area for the hypothetical San Andreas event shown on the left.

PERSONNEL SUPPORTED

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PUBLICATIONS

Liu, Q., Polet, J., Komatitsch, D., and Tromp, J., 2004. *Spectral-element moment-tensor inversions for earthquakes in southern California,* Bull. Seism. Soc. Amer., in press.

Andreas Plesch, John H. Shaw, Christine Benson, Bill Bryant, Sara Carena, Michelle Cooke, James Dolan, Gary Fuis, Eldon Gath, Lisa Grant, Egill Hauksson, Tom Jordan, Marc Kamerling, Marc Legg, Scott Lindvall, Harold Magistrale, Craig Nicholson, Nathan Niemi, Mike Oskin, Sue Perry, George Planansky, Tom Rockwell, Peter Shearer, Chris Sorlien, M. Peter Süss, John Suppe, Jerry Treiman, and Robert Yeats, 2004, *Community Fault Model (CFM) for Southern California*, Science (in review).

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•) *model for southern California based on geologic and geophysical constraints*, to be submitted to BSSA.

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